Intro to SUSY at LHC

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Outline

- SUSY characteristics

- SUSY and dark matter

- SUSY models

- LHC signatures

Why SUSY

All data consistent with SM ($g - 2$???)

SM constrained at the loop level by precise data from LEP, W mass $etc.$

New particles of mass $\lesssim 10\text{TeV}$ are constrained: EW fits, FCNC limits etc unless their couplings are very well prescribed.

Calculate with a cut off $\Lambda = 10TeV$; its much worse if you want $\Lambda = M_{Plank}$

Consider radiative corrections to the Higgs mass: calculate with a cut off $\Lambda = 10TeV$

top loop $\delta m_h^2 = \frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \sim (2TeV)^2$

W/Z loops $\delta m_h^2 \sim \alpha_w\Lambda^2 \sim -(750GeV)^2$

Higgs loop $\delta m_h^2 \sim \frac{\lambda}{16\pi^2}\Lambda^2 \sim -(1.25m_h/100GeV)^2$

But the full fits to the SM imply $m_h^2 \sim (100GeV)^2$

Fine tuning of Higgs mass seems to require something else $\sim 1\text{TeV}$

But adding new stuff can cause a conflict

It must be added in such a way that it solves the hierarchy problem without making a mess. Most extensions to the standard model fail this

SUSY to the rescue

SUSY solves it up to $\sim M_{Planck}$ by removing all quadratic divergences. This may be overkill; Most dangerous terms are top loop, Higgs loop, W/Z loops

This argument implies that some SUSY particles must have mass below 1 TeV or so, specifically, Stop, Wino.

Minimal particle content is the partners of all particles (N=1 Susy)

Scalars, one partner for each fermion spin state: Squarks (12), Sleptons (6) and sneutrinos (3 or 6)

Fermions to partner gauge bosons: gluinos(8), gauginos(4)

Two Higgs doublets and their partner fermions (4): SM anomaly from one doublet cancels the other.

Higgsino and gaugino states are mixed by EW symmetry breaking to give 2 charged ($\tilde{\chi}_i^+$) and 4 neutral states ($\tilde{\chi}_i^0$)

mixings determine decay properties

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What other stuff is (not) needed?

Avoid other fields with EW coupling. (LEP constraints)

Unbroken SUSY model has exact cancellations and mass degeneracy.

It contains gauge interactions plus Yukawa's expressed as a superpotential. Most general consistent with $SU(2) \times U(1)$

$$
\begin{aligned}
W \quad = \quad & \epsilon_{ij}\mu\hat{H}_1^i\hat{H}_2^j + \epsilon_{ij}\left[\lambda_L\hat{H}_1^i\hat{L}^{cj}\hat{E}^c + \lambda_D\hat{H}_1^i\hat{Q}^j\hat{D}^c + \lambda_U\hat{H}_2^j\hat{Q}^i\hat{U}^c\right] \\
& +\epsilon_{ij}\left[\lambda_1\hat{L}^i\hat{L}^j\hat{E}^c + \lambda_2\hat{L}^i\hat{Q}^j\hat{D}^c\right] + \lambda_3\hat{U}^c\hat{D}^c\hat{D}^c,
\end{aligned}
$$

One less parameter than SM if $\lambda_i = 0$ BUT.....

Many pitfalls to avoid

- No electroweak symmetry breaking

- Large baryon or lepton number violation. (need $\lambda_1 = \lambda_2 = 0$ and/or $\lambda_3 = 0$)

- μ is not Susy breaking, what sets its value?

- Too much CP violation

- Tachyons all $m_i^2 > 0$ except for Higgs.

- Stable heavy particles (can be good – Dark Matter)

- Problems with current constraints such as $K \to \mu\mu$, E-W constraints

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R parity

Most SUSY breaking schemes conserve R parity.

All particles even

Sparticles odd

Forces $\lambda_1 = \lambda_2 = \lambda_3 = 0$

Lightest SUSY particle (LSP) stable Dark matter – see below

R parity can be broken — but have to conserve B or L

Dark Matter

Astro data

Reduced Hubble Constant $h = 0.71^{+0.04}_{-0.03}$
Baryon Density $\Omega_b h^2 = 0.0224 \pm 0.0009$
Matter Density $\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$

- Stable particle of mass M

- Thermal equilibrium at $T >> M$:
  All particles equally abundant

- Universe expands and cools down until $T \sim M$
  If interaction rate is large enough, equilibrium is maintained and density goes to zero relative to photons
  If interaction rate is smaller, particles cannot annihilate and "freeze out"
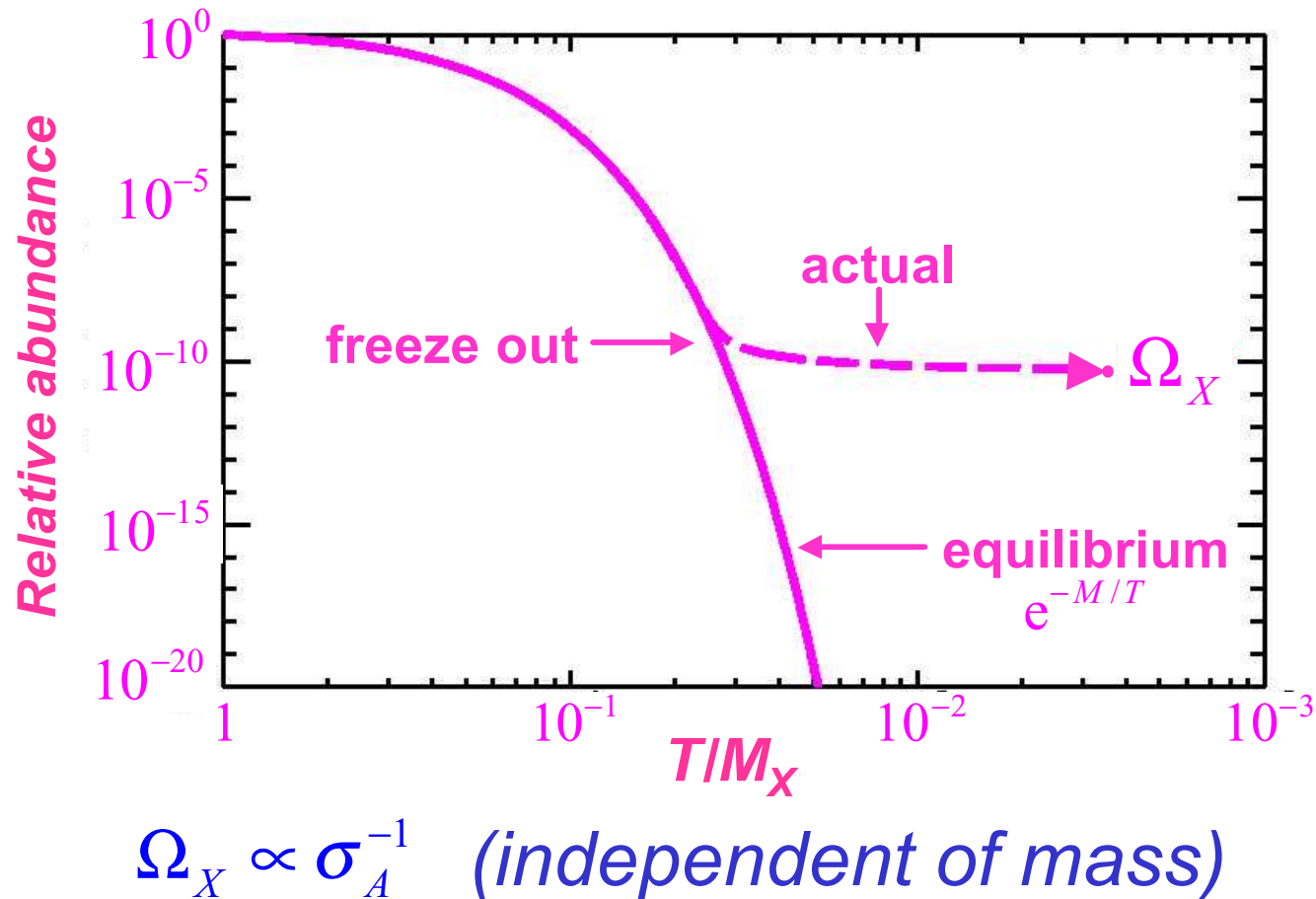
Cold thermal relics

$$\Omega_X \propto \sigma_A^{-1} \quad \text{(independent of mass)}$$

SUSY and dark matter

- Most SUSY models have unbroken R-parity the guarantees that lightest sparticle (LSP) is stable

- LSP must be neutral – candidates are $\tilde{B}, \tilde{W}^0, \tilde{H}, \tilde{\nu}$ and $\tilde{G}$

- $\tilde{\nu}$ is strongly disfavored by LEP and direct searches

- In order to be quantitative, must use a well defined model,

- LSP is usually $\tilde{B}$.

Expected range of masses and couplings is right..   there is no reason why this had to be true

Most General SUSY breaking

Very large number of parameters in the low energy theory controlled by SUSY breaking
Parametrized as coefficients of operators describing (s)particle interactions and masses.
Many new couplings
Many complex parameters $\Rightarrow$ CP violation

$$
\begin{aligned}
-\mathcal{L}_{soft} = {} & m_1^2 \mid H_1 \mid^2 + m_2^2 \mid H_2 \mid^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + \text{h.c.}) + \tilde{M}_Q^2(\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L) \\
& + \tilde{M}_u^2 \tilde{u}_R^* \tilde{u}_R + \tilde{M}_d^2 \tilde{d}_R^* \tilde{d}_R + \tilde{M}_L^2(\tilde{e}_L^* \tilde{e}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{e}_R^* \tilde{e}_R \\
& + \frac{1}{2}\left[M_3 \bar{\tilde{g}} \tilde{g} + M_2 \bar{\tilde{\omega}}_i \tilde{\omega}_i + M_1 \bar{\tilde{b}} \tilde{b} \right] + \frac{g}{\sqrt{2}M_W}\epsilon_{ij}\left[\frac{M_d}{\cos\beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* \right. \\
& \left. + \frac{M_u}{\sin\beta} A_u H_2^j \tilde{Q}^i \tilde{u}_R^* + \frac{M_e}{\cos\beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.} \right] \quad .
\end{aligned}
$$

Theory has to predict this lot and experiment to measure them!

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Getting EW symmetry breaking

Need $m_1^2 < 0$ or $m_2^2 < 0$
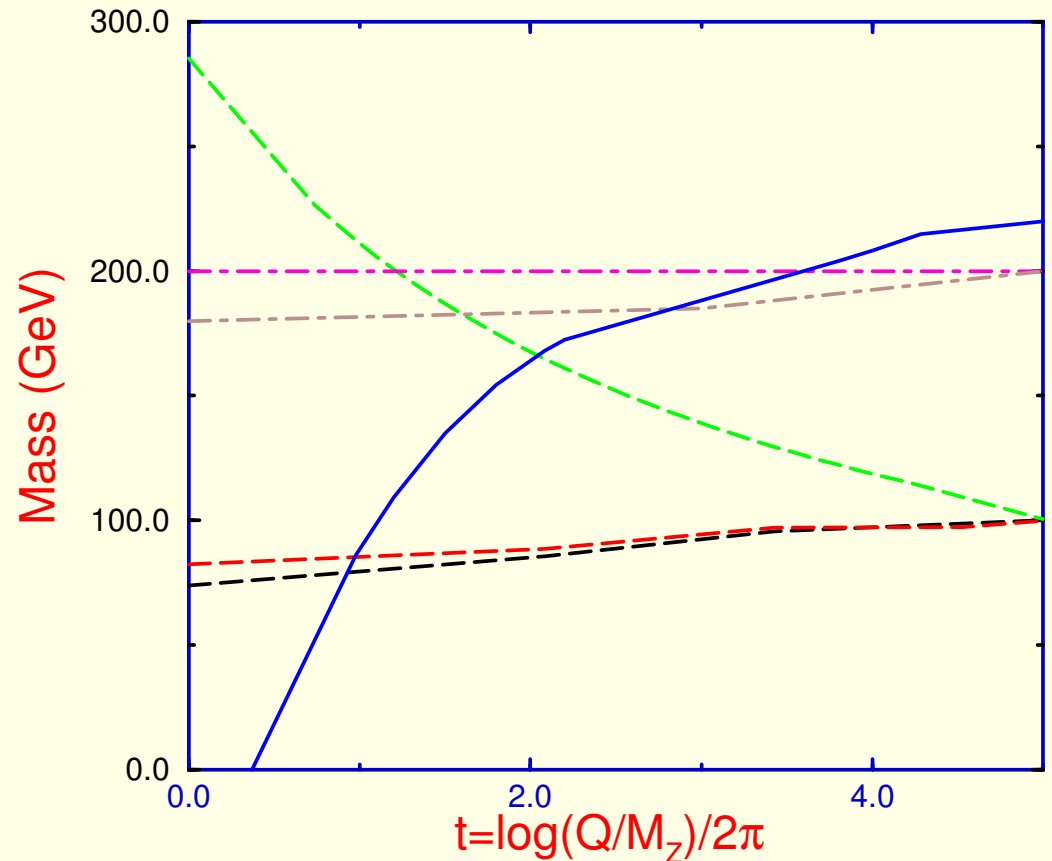
Can get this "for free"

Supposed at some high (GUT?) scale all $M_i^2 > 0$, interaction of H_2 with T via large Yukawa can drive $M_2^2 < 0$.
Requires (predicts) large top quark mass
Will work if there is "room to run"

No reason why this should have happened

SUSY cannot be broken spontaneously with only this particle content due to sum rules

$$\sum_i (-1)^F m_i^2 = 0$$

But

$$\sum_i (-1)^F m_i^2 > (TeV)^2$$

for known particles and their partners.

SUSY is broken in some "hidden sector" and then communicated to SM somehow. Models are classified by the communication mechanism and the parameters that they introduce

Smallest set of extra parameters

$M_{1/2}$: gaugino masses; all related to each other

m_0: scalar masses;

A relevant only for 3rd generation

B and μ

Higgs VeV's given by these; so B and $|\mu|$ are traded for physical parameters $\tan\beta$ and M_Z

B and μ cannot be zero

SUGRA models

Oldest idea: Try to use Gravity as the communication mechanism since we know it exists.

SUSY is broken in some sector with very heavy particles

Gravitino acquires a mass $\sim TeV$

Gravity knows nothing about E-W interactions so might guess:

Unification all scalar masses (m_0) at GUT scale

Unification all gaugino masses $(M_{1/2})$ at GUT scale universal Trilinear term A and B term with all related to gravitino mass;

Masses must then evolve to EW scale where they are observed.

Spectrum is given by 4 parameters.

$\tan\beta = v_1/v_2$, m_0, $m_{1/2}$

$sign(\mu)$ and universal Trilinear term A, important only for 3rd generation

Gluino mass strongly correlates with $m_{1/2}$, slepton mass with m_0.

R parity good – neutral LSP stable – all events have 2 LSP's in them

$\Rightarrow$ missing E_T

If μ large then $\tilde{\chi}_1^0$ is $\tilde{B}$ and $\tilde{\chi}_2^0$ is $\tilde{W}$; heavier $\tilde{\chi}$ are Higgsino

Can relax unification assumption – more parameters
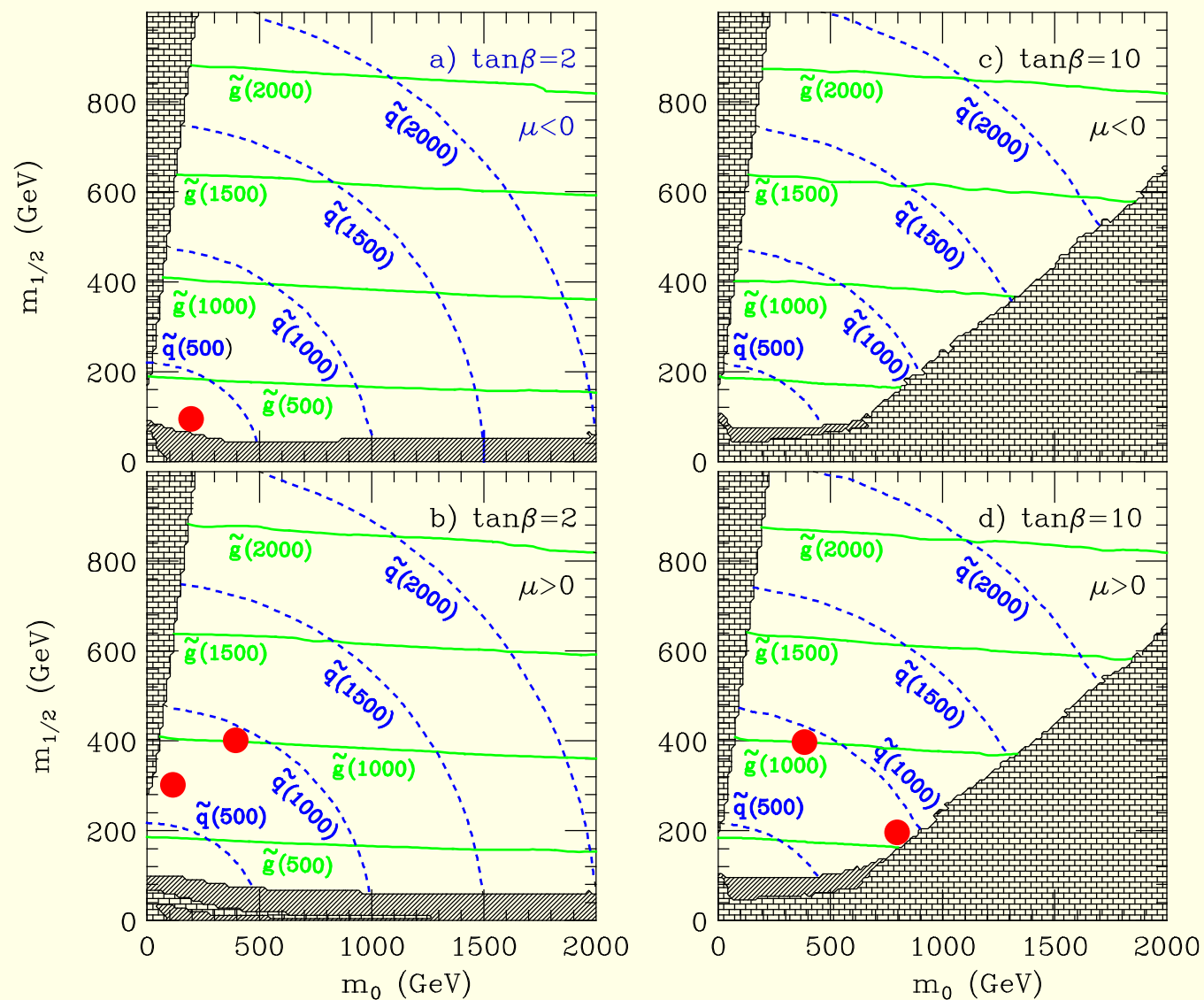
Certain regions of parameter space excluded by

Expt searches

No EW breaking

Charged LSP (assuming it's stable)

Many search limits quoted for this model

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Contours of fixed *gluino* and squark mass
IGNORE THE DOTS

Characteristic Features and signals

In general $m_{squark} > m_{slepton}$, $m_{gluino} > m_{\widetilde{W}}$

Splitting between $m_{\tilde{e}_l}$ and $m_{\tilde{e}_r}$

Stop is usually lightest squark and stau lightest slepton.

LSP must be neutral if stable; its usually $\tilde{B}$

Stable LSP $\Rightarrow$ Missing E_T

Complicated final states will dominate LHC $e.g.$

$$\tilde{g} \to \overline{q}\tilde{q} \to \overline{q}q\tilde{\chi}_2^0 \to \overline{q}q\tilde{\tau}\tau \to \overline{q}q\tilde{\chi}_2^0 \to \overline{q}q\tau\tilde{\chi}_1^0\tau$$

Nice features of SUGRA model

Natural dark matter candidate with right properties
Neutral LSP can be Cold Dark Matter

But parameter space is getting
restricted by WMAP (small blue region)

Ellis, Olive...

details rather model dependent

$\tan \beta = 10 , \mu > 0$
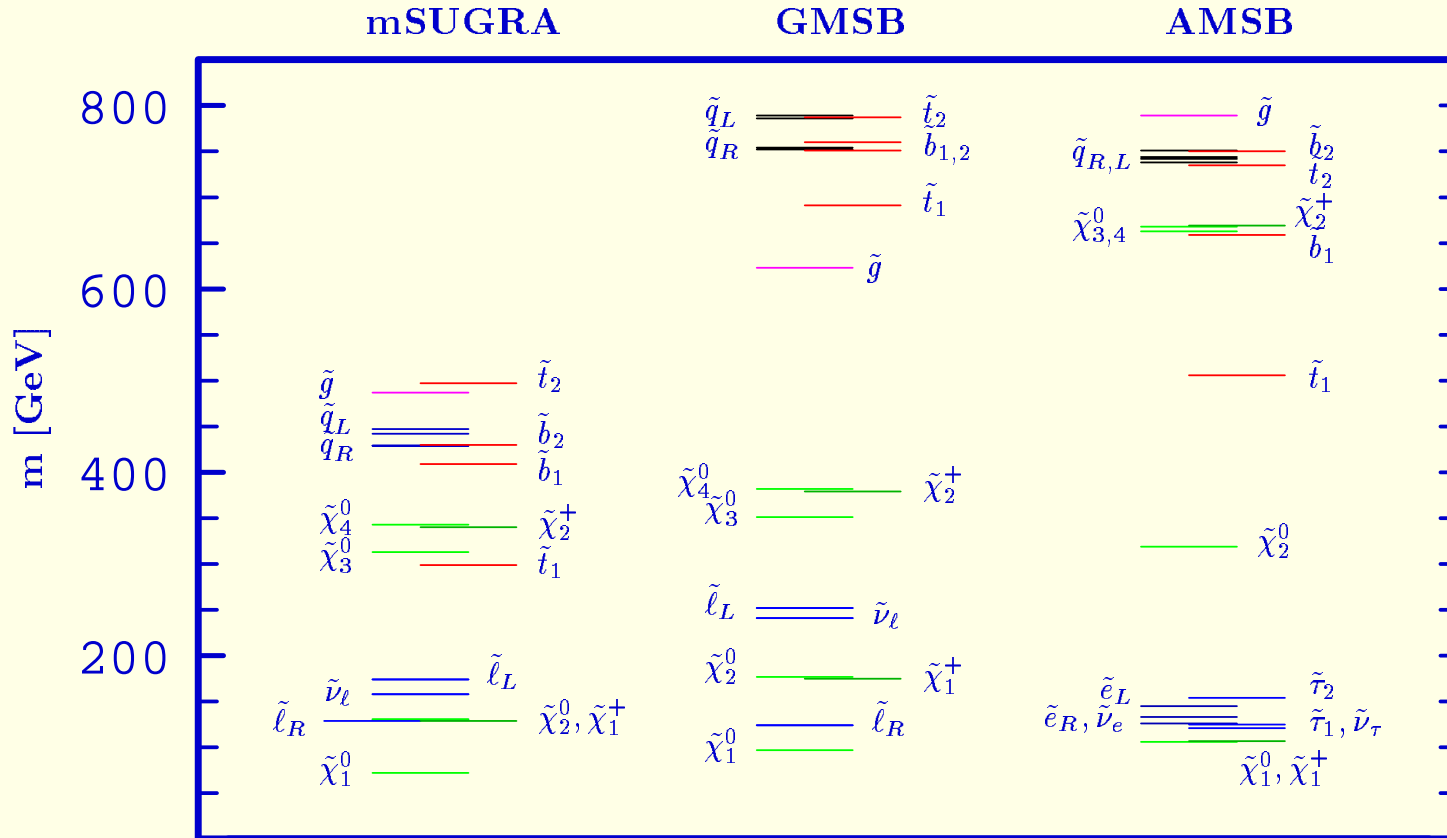
$m_h = 114$ GeV

$m_{\chi^\pm} = 104$ GeV

m_0 (GeV)

$m_{1/2}$ (GeV)
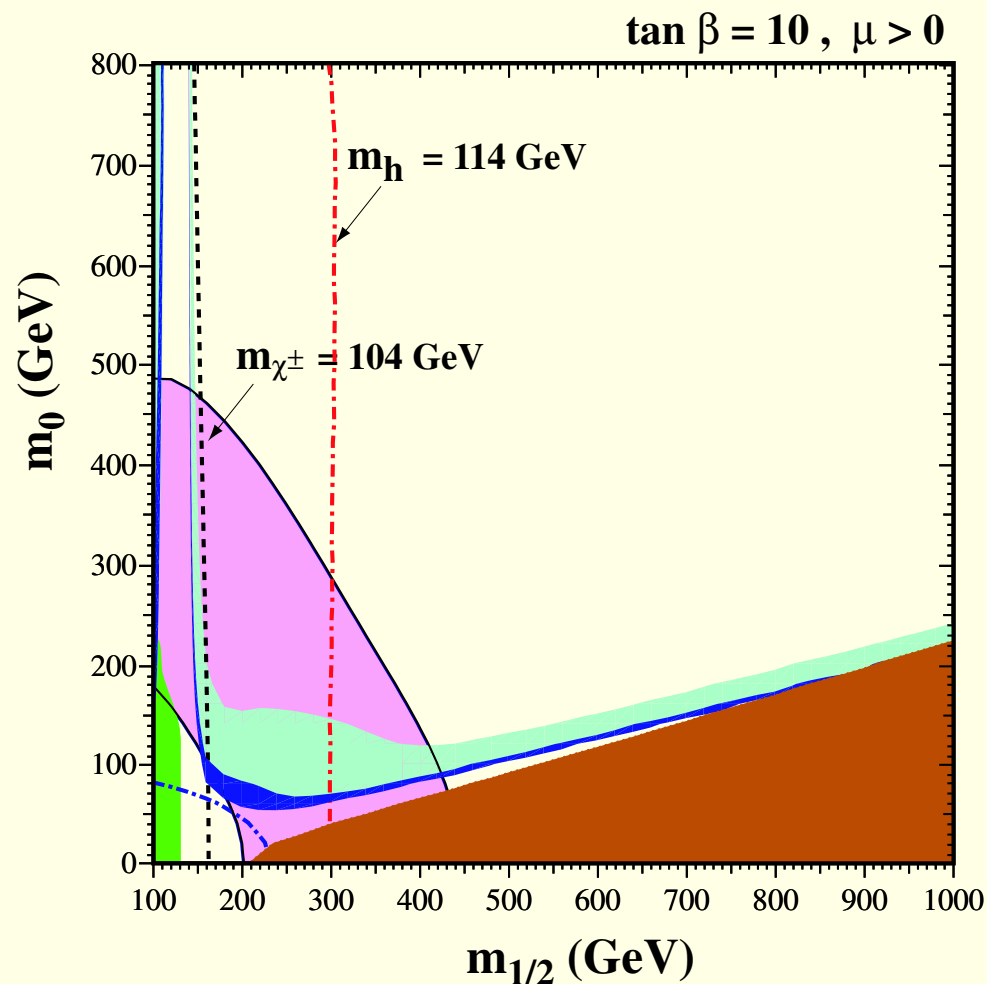
Timeout – some typical spectra

Figure 3.0.1: *Examples of mass spectra in mSUGRA, GMSB and AMSB models for* $\tan\beta = 3$, $sign\,\mu > 0$. *The other parameters are* $m_0 = 100$ *eV*, $m_{1/2} = 200\,GeV$ *for mSUGRA*; $M_{\mathrm{mess}} = 100\,TeV$, $N_{\mathrm{mess}} = 1$, $\Lambda = 70\,TeV$ *for GMSB*; *and* $m_0 = 200\,GeV$, $m_{3/2} = 35\,TeV$ *for AMSB*.

How do we sort it out?

SUSY breaking sector not observable directly

Must be inferred from pattern of susy breaking parameters, masses and couplings.

<div align="center">Critical tests</div>

Is there missing E_T? "yes" $\rightarrow$ No Rparity

Do gaugino masses fit a GUT unification scheme? "no" $\rightarrow$ not SUGRA

Yukawa couplings and mixings of third generation squarks and sleptons?

Is there flavor violation in the slepton sector? "yes" $\rightarrow$ Neutrino masses?

Is there an inverted hierarchy in the squark sector?

Are there quasi stable charged particles? "yes" $\rightarrow$ GMSB

Will require large number of measurements

Characteristic SUSY signatures at LHC

Not all present in all models

- $\not{E}_T$

- High Multiplicity of large p_t jets

- Many isolated leptons

- Copious b production

- Large Higgs production

- Isolated Photons

- Quasi-stable charged particles

N.B.Production of heavy objects implies subset these signals

Everything is produced at once.

squarks and gluinos proabably have largest rates

Production of Sparticles with only E-W couplings (e.g sleptons, Higgs) may be dominated by decays of squarks not direct production.

Dominant backgrounds at LHC are combinatorial from SUSY events themselves.

Example of inclusive signal

Produces events with jets and missing transverse energy

- Select events with at least 4 jets and Missing E_T
  A simple variable:
  $$M_{\mathrm{eff}} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + \not{E}_T$$

- At high M_{eff} non-SM signal rises above background (shaded histogram)
  Note scale – huge event rate

- Peak in M_{eff} distribution correlates well with SUSY mass scale
  $$M_{\mathrm{SUSY}} = \min(M_{\widetilde{u}}, M_{\widetilde{g}})$$
  This example has susy masses around 700 GeV
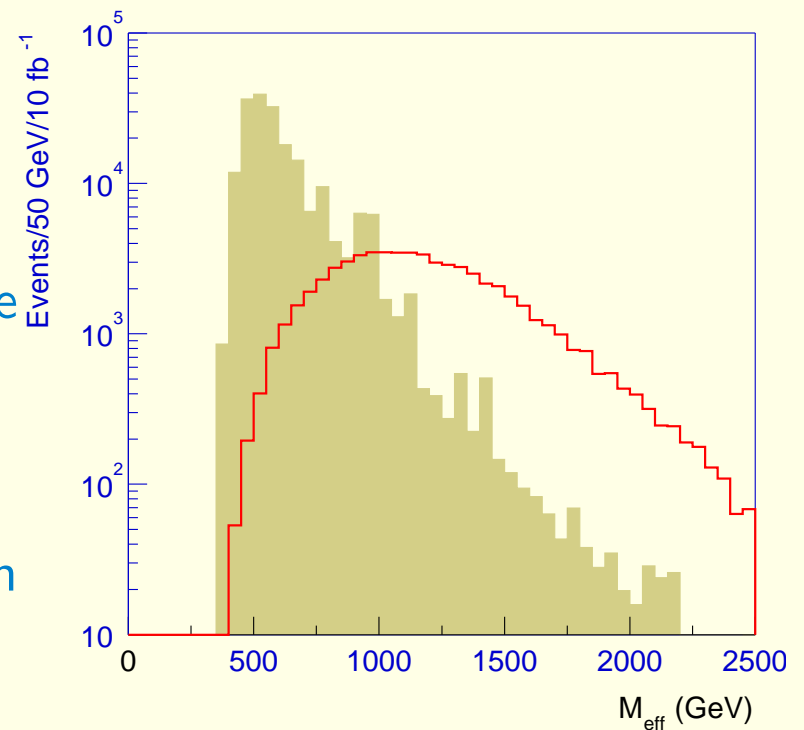
Accessible masses at LHC

Very large range of accessible masses in inclusive signals $jets + \rlap{/}{E}_T$ etc Example $- 0.1 fb^{-1}$ discovers gluino of mass 1.4 TeV This is 1 year at 1/1000 of design luminosity!

Covers all interesting theoretical range $m_{\tilde{g}} \lesssim 2.5 \, \text{TeV}$
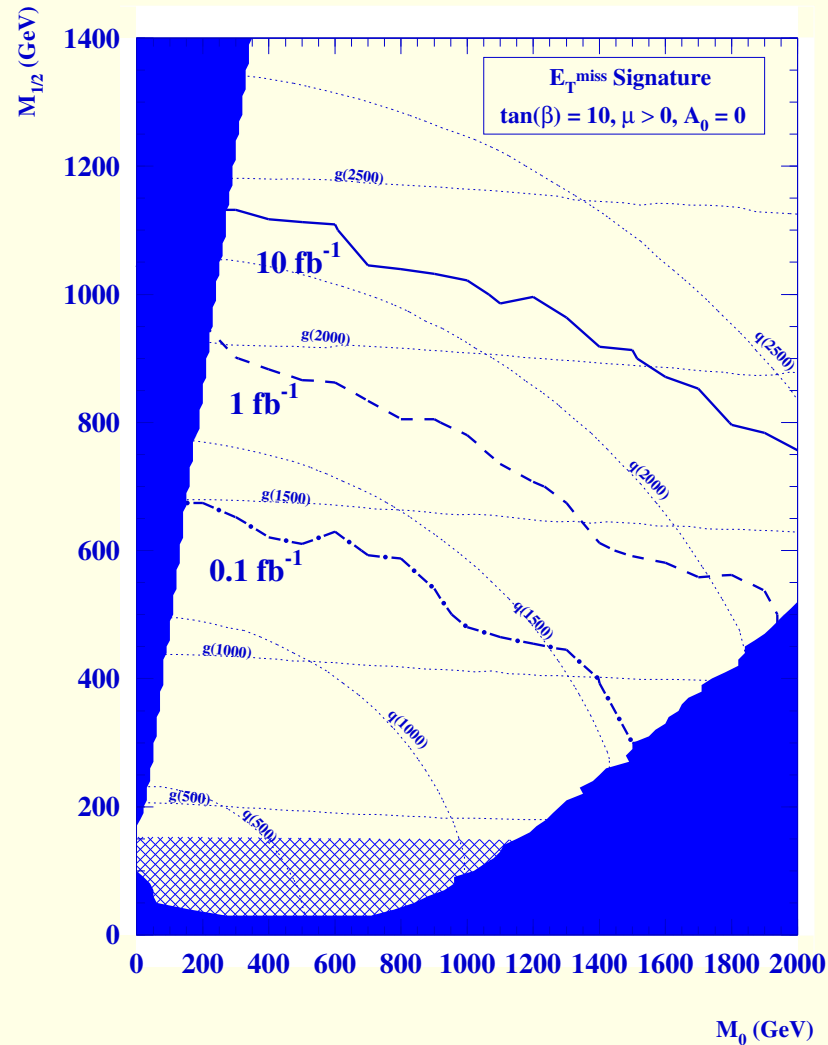
Need to be ready to do physics at day one

Characteristic Decays

Illustrate techniques by choosing examples from case studies.

Both $\widetilde{q}$ and $\widetilde{g}$ produced; one decays to the other

Weak gauginos ($\widetilde{\chi}_i^0, \widetilde{\chi}_i^{\pm}$) then produced in their decay. $e.g.$ $\widetilde{q_L} \to \widetilde{\chi}_2^0 q_L$

Two generic features
$\chi_2^0 \to \chi_1^0 h$ or
$\chi_2^0 \to \chi_1^0 \ell^+ \ell^-$ possibly via intermediate slepton $\chi_2^0 \to \widetilde{\ell^+}\ell^- \to \chi_1^0 \ell^+ \ell^-$
Former tends to dominate if kinematically allowed.

Use these characteristic decays as a starting point for mass measurements

Many SUSY particles can then be identified by adding more jets/leptons

Decays to Higgs bosons

If $\chi_2^0 \to \chi_1^0 h$ exists then this final state followed by $h \to b\bar{b}$ results in discovery of Higgs at LHC.

In these cases $\sim 20\%$ of SUSY events contain $h \to b\bar{b}$

Event selection

$\not{E}_T > 300 \, \text{GeV}$

≥ 2 jets with $p_T > 100 \, \text{GeV}$ and ≥ 1 with $|\eta| < 2$
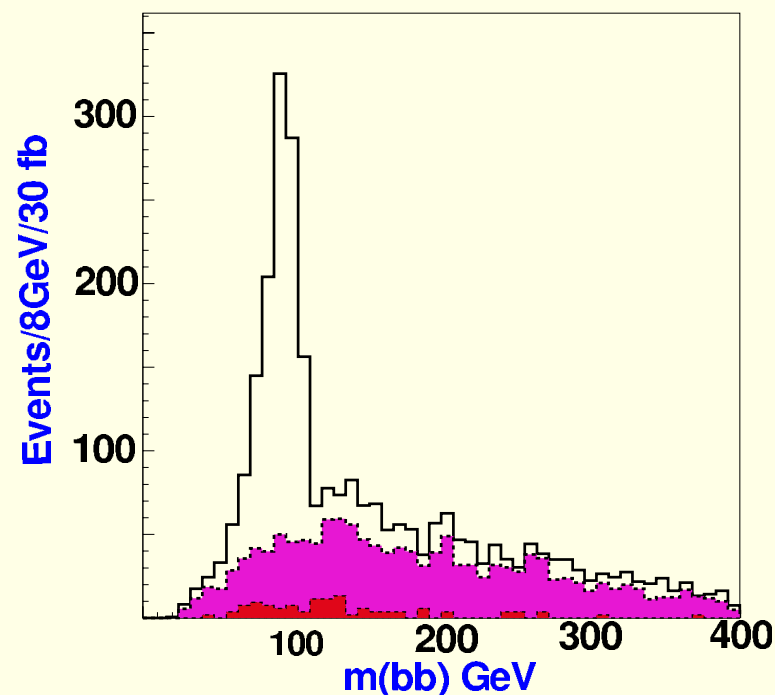
No isolated leptons (suppresses $t\bar{t}$)

Only 2 b-jets with $p_{T,b} > 55$ GeV and $|\eta| < 2$

$\Delta R_{b\bar{b}} < 1.0$ (suppresses $t\bar{t}$)

Clear peak in $b\bar{b}$ mass

Very small standard model background (pale)

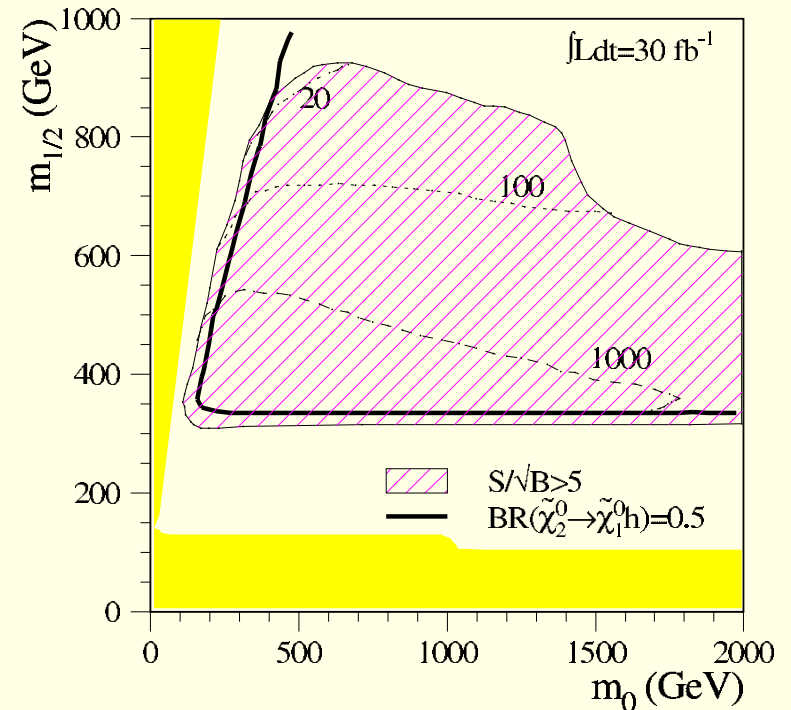Dominant background is other SUSY decays (dark)

Generally applicable

This method works over a large region of parameter space in the SUGRA Model

Hatched region has $S/\sqrt{B} > 5$

Contours show number of reconstructed Higgs
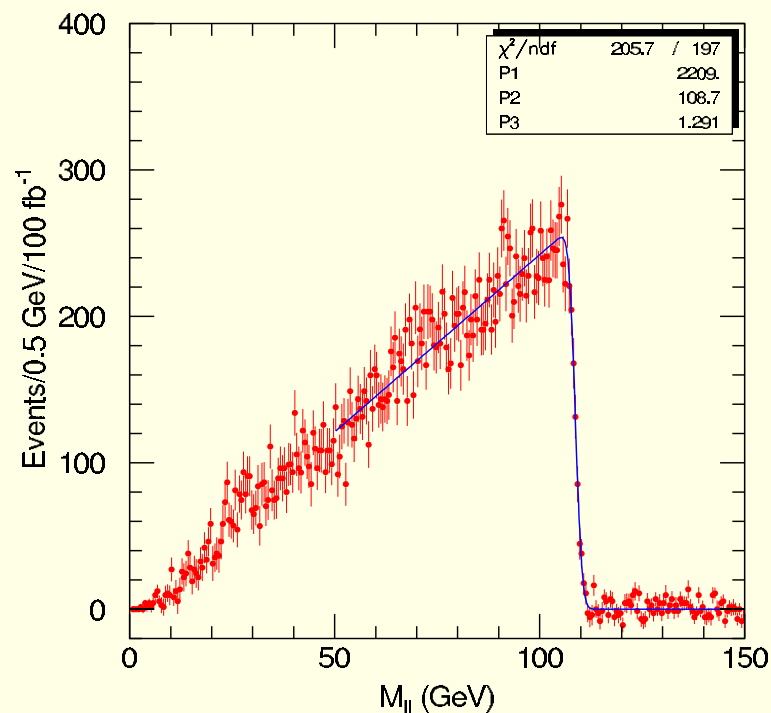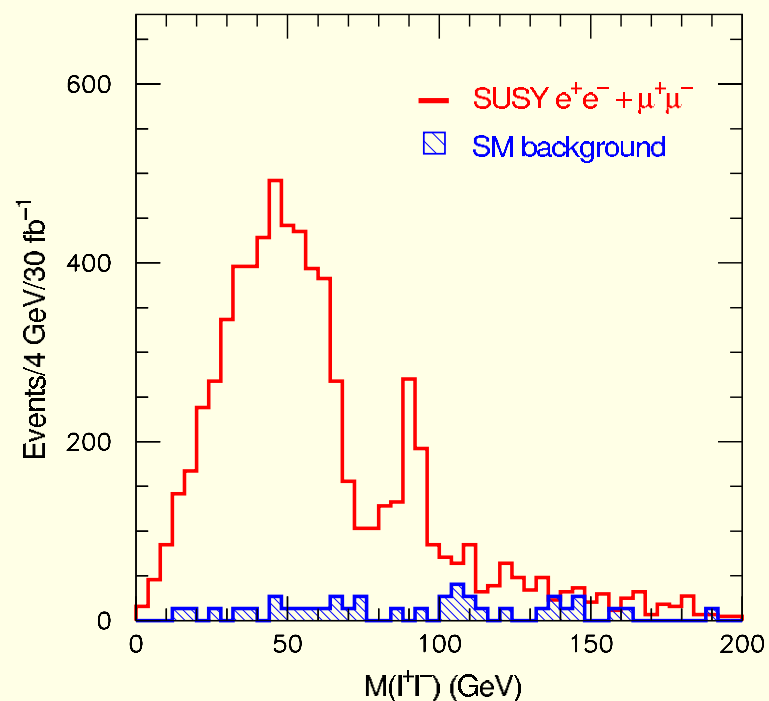
Channel is closed at low $m_{1/2}$

Another example

Isolated leptons indicate presence of t, W, Z, weak gauginos or sleptons
Key decays are $\widetilde{\chi}_2 \to \widetilde{\ell}^+\ell^-$ and $\widetilde{\chi}_2 \to \widetilde{\chi}_1\ell^+\ell^-$
Mass of opposite sign same flavor leptons is constrained by decay

Decay via real slepton: $\widetilde{\chi}_2 \to \widetilde{\ell}^+\ell^-$
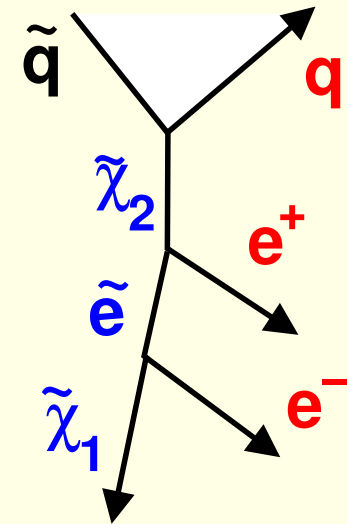Plot shows $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$

Decay via virtual slepton: $\widetilde{\chi}_2 \to \widetilde{\chi}_1\ell^+\ell^-$
and Z from other SUSY particles

Building on Leptons

Decay $\tilde{q}_L \to q\widetilde{\chi}_2^0 \to q\widetilde{\ell}\ell \to q\ell\ell\widetilde{\chi}_1^0$
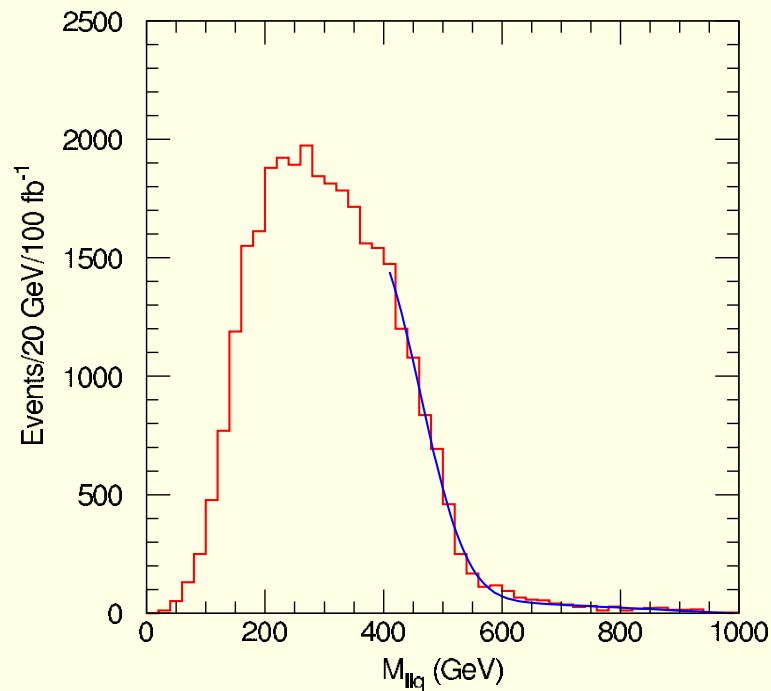
Identify and measure decay chain
- 2 isolated opposite sign leptons; $p_t > 10$ GeV
- ≥ 4 jets; one has $p_t > 100$ GeV, rest $p_t > 50$ GeV
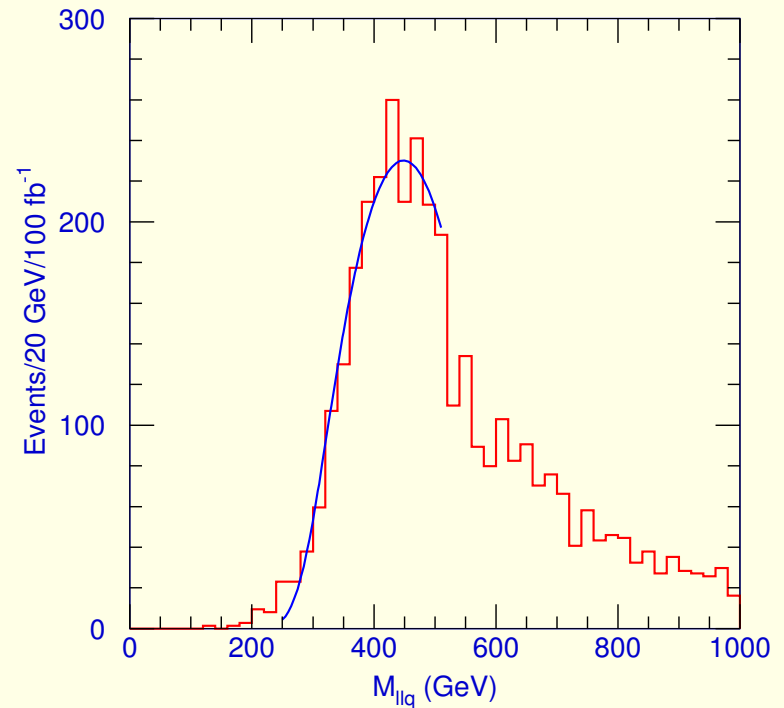- $\not{E}_T > max(100, 0.2M_{eff})$

Mass of $q\ell\ell$ system has max at

$$M_{\ell\ell q}^{\max} = [\frac{(M_{\tilde{q}_L}^2 - M_{\widetilde{\chi}_2^0}^2)(M_{\widetilde{\chi}_2^0}^2 - M_{\widetilde{\chi}_1^0}^2)}{M_{\widetilde{\chi}_2^0}^2}]^{1/2} = 552.4\,\mathrm{GeV}$$

and min at 271 GeV

smallest mass of possible $\ell\ell jet$ combinations
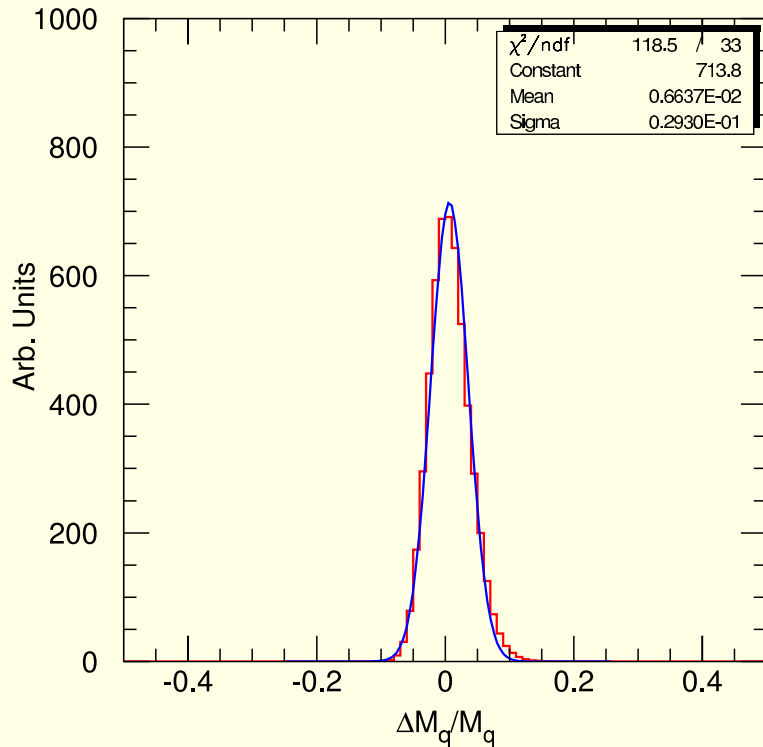
Kinematic structure clearly seen

largest mass of possible $\ell\ell jet$ combinations

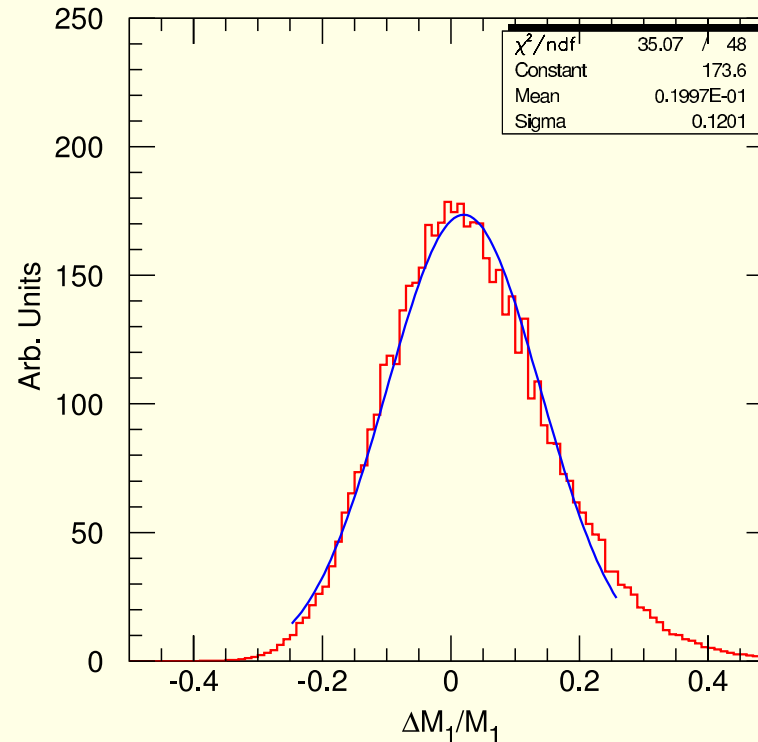Can now solve for the masses. Note that no model is needed

Very naive analysis has 4 constraints from $lq, llq_{upper}, llq_{lower}, ll$ masses

4 Unknowns, $m_{\tilde{q}_L}, m_{\tilde{e}_R}, m_{\tilde{\chi}^0_2}, m_{\tilde{\chi}^0_1}$

Errors are 3%, 9%, 6% and 12% respectively

χ^2/ndf	118.5 / 33
Constant	713.8
Mean	0.6637E-02
Sigma	0.2930E-01

χ^2/ndf	35.07 / 48
Constant	173.6
Mean	0.1997E-01
Sigma	0.1201

Squark mass   LSP mass

Mass of unobserved LSP is determined

Comments and Conclusions

SUSY is well motivated

Large number of signals

Many cases studied

Still some fast simulation studies needed

Most effort now focussed on full simulation $\rightarrow$ Frank

An era is about to end

Low energy SUSY has provided employment for > 20 years

It will be discovered or die in the next 6 years.

Extra work

Out of this world breaking I – gaugino mediation

Motivated by theory of extra dimensions. Recall that strings need extra dim, so may not be totally crazy.

5D theory with 2 4-d boundaries (branes). We live on one. SUSY is spontaneously broken on the other.

Quarks and leptons trapped on our brane. Gauge fields propagate in all 5-d.

Gauginos get mass since they interact with the other brane.

At some compactification scale $m_0 = A = 0$, natural to assume a unification so only parameter is $M_{1/2}$

Scalar masses arise at one loop from gaugino interactions hence "gaugino mediated".

No flavor problem
Stau is light: may be the only
slepton is gluino decay
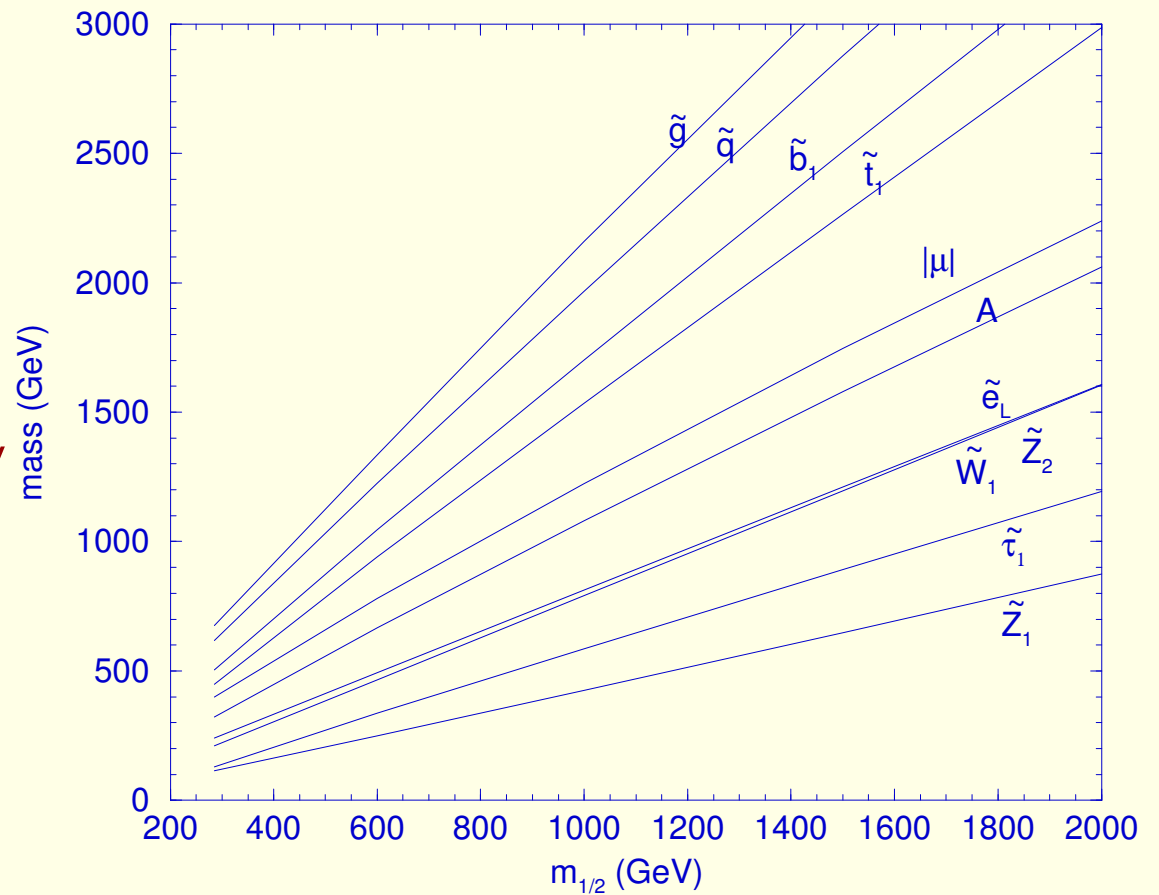
Out of this world breaking II – boundary conditions

Again theory of extra dimensions.   Barbieri, Hall, Ratazzi, Nomuara....

$5th$ dimension is compactified with boundary conditions that violate SUSY.

SUSY is explicitly broken but only at a single point

Low energy spectrum is not MSSM (h violates
the bound discussed above)

SUSY spectrum is compressed

Quasi-stable stop

Dark matter?

KK excitations

susy states

SM states

Anomaly mediated breaking

Superconformal anomaly always present

predicts sparticle masses in terms of $m_{3/2}$ <small>Randall, Sundrum, Luty, Giudice, Wells, Murayama, Jones...</small>

Generates gaugino masses with very differant structure

$$M_i = \frac{\beta(g_i)}{2g_i^2} m_{3/2}$$

Simplest version predicts tachyonic sleptons!

Some other SUSY breaking mechanism must be present to get realistic spectrum

Add universal squark masses (mAMSB) or new very heavy fields (DAMSB)

AMSB only – Most important feature $M_3 > M_1 > M_2 \Rightarrow$ LSP is a $\tilde{W}^0$ and almost degenerate with $\tilde{\chi}_1^+$

Critical prediction $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$ with $c\tau < 10$ cm   But very model dependent.

Sleptons are lighter than squarks $\tilde{q}_r \rightarrow \tilde{\chi}_2^0 q$ and $\tilde{q}_l \rightarrow \tilde{\chi}_1^0 q$, *i.e. opposite* to SUGRA and GMSB.

Gravitino mass is $\sim$ TeV, irrelevant to terrestrial experiments.

$\tilde{q}_r \rightarrow \tilde{\chi}_2^0 q$ and $\tilde{q}_l \rightarrow \tilde{\chi}_1^0 q$, *i.e. opposite* to SUGRA and GMSB.

Gauge Mediated breaking

Problem with SUGRA is that gravity knows nothing about EW interactions.

Why do the flavors align?: quark flavor states are determined by EW structure; squarks by both SUSY breaking and EW. In general expect large flavor changing neutral currents and lepton disasters like $\mu \to e\gamma$

Aims to solve FCNC problem by using gauge interactions instead of Gravity to transmit SUSY breaking Messenger Sector consists of some particles (X) that have SM interactions and are aware of SUSY breaking.

$M_i^2 = M^2 \pm F_A$

Gaugino masses at 1-loop

$$M_{\widetilde{g}} \sim \alpha_s N_X \Lambda$$

Squark and Slepton masses at 2-loop, but its $mass^2$ so

$$M_{\widetilde{e}} \sim \alpha_W \sqrt{N_X} \Lambda$$

True LSP is a (almost) massless Gravitino

Sparticles decay as in SUGRA, then "NLSP" decays to $\tilde{G}$
lifetime model dependent

NLSP does not have to be neutral; can be long lived

Lacks a natural dark matter candidate.

Charateristic signals in GMSB

Lightest superpartner is unstable and decays to Gravitino ($\tilde{G}$)

Either neutral

$\chi_1^0 \to \gamma\tilde{G} : c\tau \sim C^2(100 \text{ GeV}/M_{\chi_1^0})^5(\Lambda/180\text{TeV})^2(M_M/180\text{TeV})^2\text{mm}$

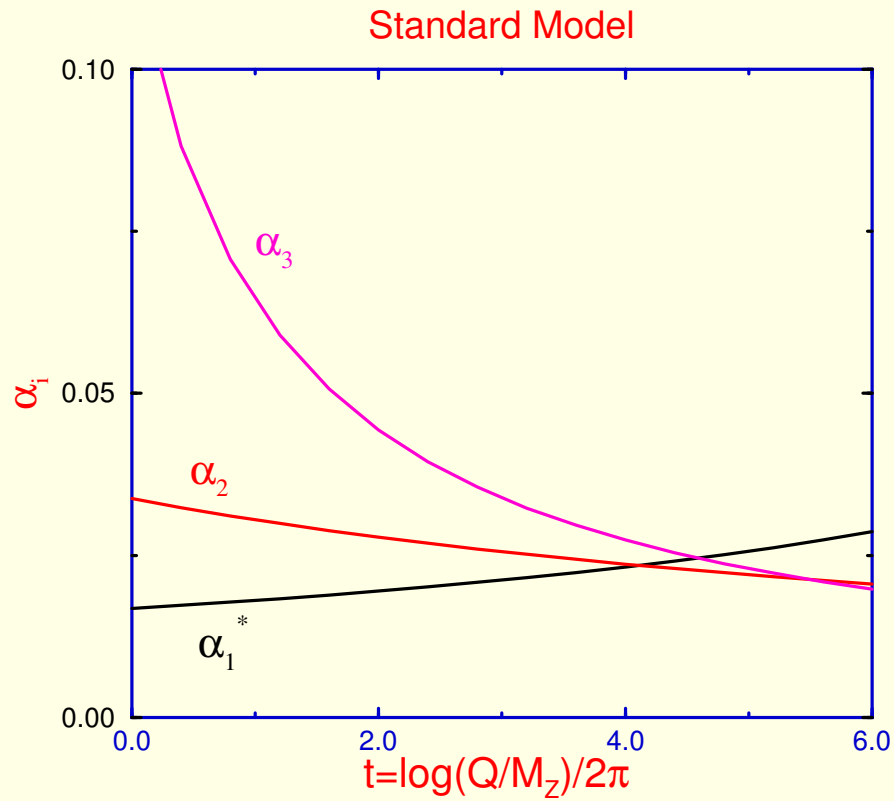$\Rightarrow$ extra photons ("G1a") or similar signals to SUGRA ("G1b") depending on lifetime

Or charged

Almost always slepton: $\tilde{e_R} \to e\tilde{G}$

No Missing E_T if $c\tau$ large: events have a pair of massive stable charged particles
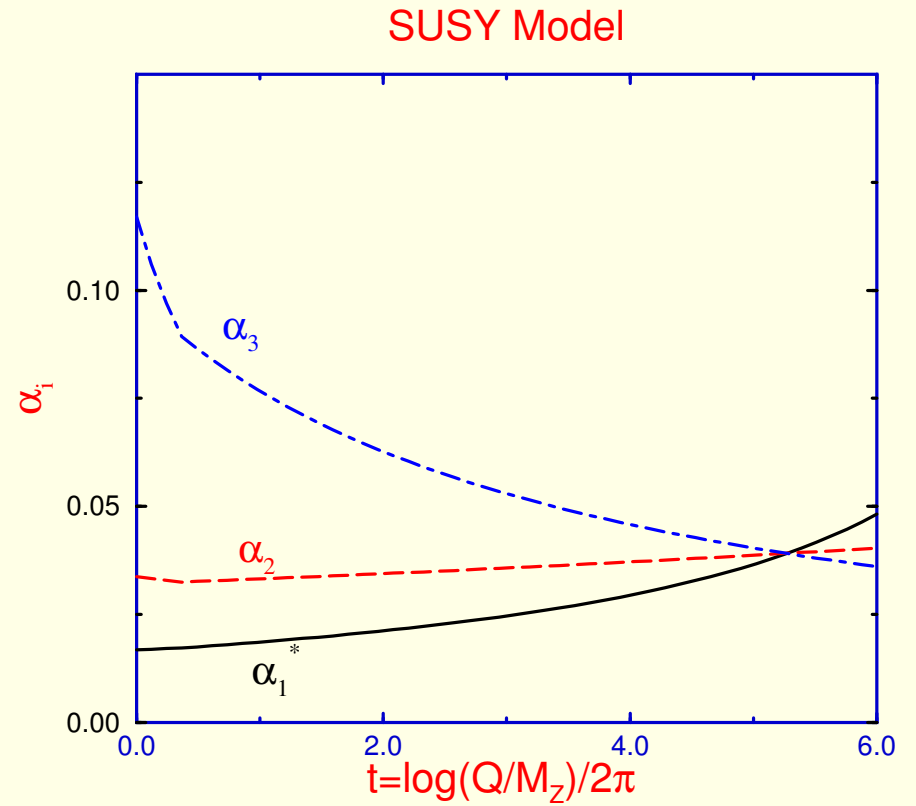
Large lepton multiplicity if $c\tau$ small.

Discovery and measurement in these cases is trivial

Susy helps unification

without susy   with susy

Higgs particles and masses

Three mass eigenstates h, H, A and $H^{\pm}$

Properties predicted in terms of above parameters.

Lightest h is bounded independent of susy breaking

Not far above LEP limit

Properties of h similar to standard model

Figure legend:

maximal mixing
$\mu = -200$ GeV
$M_{\text{SUSY}} = 1$ TeV

$H^{\pm}$ $(----)$
H $(\underline{\quad\quad})$
h $(-\cdot-\cdot-)$

$\tan \beta = 3$

Axis: Higgs Mass (GeV) vs m_A (GeV)

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